



Maternal Polybrominated Diphenyl Ether (PBDE) Exposure and Thyroid Hormones in Maternal and Cord Sera: The HOME Study, Cincinnati, USA

**Ann M. Vuong, Glenys M. Webster, Megan E. Romano,
Joseph M. Braun, R. Thomas Zoeller, Andrew N. Hoofnagle,
Andreas Sjödin, Kimberly Yolton, Bruce P. Lanphear,
and Aimin Chen**

<http://dx.doi.org/10.1289/ehp.1408996>

Received: 24 July 2014

Accepted: 14 April 2015

Advance Publication: 17 April 2015

This article will be available in its final, 508-conformant form 2–4 months after Advance Publication. If you need assistance accessing this article before then, please contact ehp508@niehs.nih.gov. Our staff will work with you to assess and meet your accessibility needs within 3 working days.



National Institute of
Environmental Health Sciences

Maternal Polybrominated Diphenyl Ether (PBDE) Exposure and Thyroid Hormones in Maternal and Cord Sera: The HOME Study, Cincinnati, USA

Ann M. Vuong,¹ Glenys M. Webster,² Megan E. Romano,³ Joseph M. Braun,³ R. Thomas Zoeller,⁴ Andrew N. Hoofnagle,⁵ Andreas Sjödin,⁶ Kimberly Yolton,⁷ Bruce P. Lanphear,² and Aimin Chen¹

¹Division of Epidemiology, Department of Environmental Health, University of Cincinnati College of Medicine, Cincinnati, Ohio, USA; ²Child and Family Research Institute, BC Children's and Women's Hospital and Faculty of Health Sciences, Simon Fraser University, Vancouver, British Columbia, Canada; ³Department of Epidemiology, Brown University School of Public Health, Providence, Rhode Island, USA; ⁴Department of Biology, University of Massachusetts, Amherst, Massachusetts, USA; ⁵Department of Laboratory Medicine, University of Washington, Seattle, Washington, USA; ⁶Division of Laboratory Sciences, National Center for Environmental Health, Centers for Disease Control and Prevention, Atlanta, Georgia, USA; ⁷Division of General and Community Pediatrics, Department of Pediatrics, Cincinnati Children's Hospital Medical Center, Cincinnati, Ohio, USA

Address correspondence to Aimin Chen, Division of Epidemiology, Department of Environmental Health, University of Cincinnati College of Medicine, P.O. Box 670056, Cincinnati, OH 45267-0056 USA. Telephone: 513-558-2129. Fax: 513-558-4397. E-mail: aimin.chen@uc.edu

Running title: Maternal PBDE exposure and thyroid hormones

Acknowledgments: This work was supported by grants from the National Institute of Environmental Health Sciences (NIEHS P01 ES11261, R01 ES014575, R01 ES020349, and R00 ES020349). The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the NIEHS or the Centers for Disease Control and Prevention (CDC).

Competing financial interests: Dr. Lanphear served as an expert witness and as a consultant to the California Attorney General's Office, but has not personally received compensation for these services. Dr. Lanphear also served as a paid consultant on a US Environmental Protection Agency research study and to the California Department of Toxic Substance Control. Dr. Braun was financially compensated for conducting a re-analysis of the international pooled study of lead exposure for the plaintiffs in a public nuisance case. None of the other authors has any actual or potential competing financial interests.

Abstract

Background: Polybrominated diphenyl ethers (PBDEs) reduce blood concentrations of thyroid hormones in laboratory animals, but it is unclear whether PBDEs disrupt thyroid hormones in pregnant women or newborn infants.

Objectives: We investigated the relationship between maternal PBDE levels and thyroid hormone concentrations in maternal and cord sera.

Methods: We used data from the Health Outcomes and Measures of the Environment Study, a prospective birth cohort of 389 pregnant women in Cincinnati, Ohio who were enrolled from 2003-2006 and delivered singleton infants. Maternal serum PBDE concentrations were measured at enrollment (16±3 weeks of gestation). Thyroid hormone concentrations were measured in maternal serum at enrollment (n=187) and in cord serum samples (n=256).

Results: Median maternal serum concentrations of BDE-28 and -47 were 1.0 and 19.1 ng/g lipid, respectively. A 10-fold increase in BDE-28 and BDE-47 concentrations was associated with a 0.85 µg/dL (95% Confidence Interval [CI]: 0.05, 1.64) and 0.82 µg/dL (95% CI 0.12, 1.51) increase in maternal total thyroxine concentrations (TT₄), respectively. Both congeners were also positively associated with maternal free thyroxine (FT₄). We also observed positive associations between BDE-47 and maternal total and free triiodothyronine (TT₃ and FT₃). A 10-fold increase in BDE-28 was associated with elevated FT₃ concentrations (β =0.14 pg/ml, 95% CI 0.02, 0.26). In contrast, maternal PBDE levels were not associated with thyroid hormone concentrations in cord serum.

Conclusions: These findings suggest maternal PBDE exposure, particularly BDE-28 and -47, are associated with maternal concentrations of T₄ and T₃ during pregnancy.

Introduction

Polybrominated diphenyl ethers (PBDEs), synthetic flame retardants, have been used in the manufacture of consumer products, including furniture foam, carpet padding, and electronics. Because they are semivolatile and are not covalently bound to consumer products, PBDEs readily leach out into the environment. North Americans have the highest human concentrations of PBDEs globally, with serum levels 10 to 100-times higher than those observed among Europeans and Japanese (Costa and Giordano 2007).

PBDEs can reduce blood levels of thyroid hormones in laboratory animals (Darnerud 2008). Thyroxine (T_4) was significantly reduced among rodents pre- and postnatally exposed to PBDEs (Kim et al. 2009a; Zhou et al. 2002), suggesting a hypothyroxinemic or hypothyroid effect. Possible mechanisms include competitive binding to the thyroid transport protein transthyretin (TTR) and thyroid hormone receptors (Meerts et al. 2000; Richardson et al. 2008), and increasing T_4 metabolism and clearance by inducing thyroxine glucuronidation via uridine diphosphate glucuronosyltransferase enzymes (Zhou et al. 2002).

PBDEs may also interfere with adult human thyroid hormone levels, though studies suggest a hyperthyroid rather than a hypothyroid effect (Dallaire et al. 2009; Hagmar et al. 2001; Turyk et al. 2008). Because thyroid hormones are essential for fetal growth and neurological development, it is particularly important to test whether PBDEs alter thyroid hormone levels during pregnancy (Forhead and Fowden 2014). There is an increased demand on the maternal thyroid gland during pregnancy as the fetus relies predominately on the maternal supply of thyroid hormones until approximately 18-22 weeks gestation (Morreale de Escobar et al. 2000). The fetus continues to depend on maternal inputs for thyroid hormone stabilization even after endogenous fetal production of thyroid hormones (de Escobar et al. 2004). Perturbations in

thyroid hormone levels during gestation may result in altered neurobehavior. Lower levels of maternal T₄ have been linked to neurodevelopmental deficits (Henrichs et al. 2013; Julvez et al. 2013), and maternal subclinical hypothyroidism has been associated with an increased risk of adverse pregnancy outcomes, including spontaneous abortion, placental abruption, and preterm delivery (Mannisto et al. 2013).

Several epidemiologic studies have examined associations between PBDEs and thyroid hormone levels in maternal and cord sera (see Supplemental Material, Table S1). Though most studies have reported an association between PBDEs and one or more thyroid hormones, results are inconsistent (Abdelouahab et al. 2013; Chevrier et al. 2010; Herbstman et al. 2008; Kim et al. 2009b; Kim et al. 2011; Lin et al. 2011; Mazdai et al. 2003; Roze et al. 2009; Stapleton et al. 2011; Zhang et al. 2010; Zota et al. 2011). Further, most have small to modest sample sizes, and only two have measured maternal thyroid hormones before full functioning of the fetal thyroid axis (Abdelouahab et al. 2013; Zhang et al. 2010).

Given the inconsistent results of studies linking PBDEs and thyroid hormones and the importance of thyroid hormones during pregnancy, we examined the relationships between prenatal PBDE exposure and thyroid hormone concentrations measured in maternal serum at 16±3 weeks of gestation and in cord serum following delivery.

Methods

Study participants and design

We used data from the Health Outcomes and Measures of the Environment (HOME) Study, an ongoing prospective pregnancy and birth cohort (<http://www.cincinnatichildrens.org/research/divisions/e/environmental/study/default/>). Nine

prenatal clinics in the Cincinnati, Ohio (USA) metropolitan area served as the source population for pregnant women. Women were enrolled in the study between March 2003 and January 2006 if they were: ≥ 18 years of age; residing in a house built before 1978 (a criterion relating to a goal of the larger HOME Study examining lead exposures); intending to continue prenatal care and deliver at any of the collaborating obstetric practices and hospitals; and HIV negative. Women receiving seizure, thyroid, or chemotherapy/radiation medications were ineligible to participate. Letters were mailed to women ≥ 18 years who were living in houses built before 1978 ($n=5,184$). Of 1,263 eligible women, 468 enrolled and provided informed consent, and 389 remained in the study until they delivered live singleton infants. We further restricted the sample to women with PBDE concentrations measured at enrollment (16 ± 3 weeks of gestation) and thyroid hormone levels measured in either maternal ($n=187$) or cord serum ($n=256$). The study protocol was approved by the Institutional Review Board at the Cincinnati Children's Hospital Medical Center and the Centers for Disease Control and Prevention (CDC). All participants provided written informed consent for themselves and their children prior to study enrollment.

Data collection

We collected sociodemographic, behavioral, and general health characteristics using standardized questionnaires and interviews administered following consent. Chart abstraction after delivery was used to obtain data on obstetric history and delivery.

Concentrations of PBDEs were measured in maternal serum samples collected at approximately 16 weeks gestation. Serum was separated from clotted blood samples and stored at -80°C until analysis. Concentrations of PBDEs (BDE-17, -28, -47, -66, -85, -99, -100, -153, -154, and -183) and polychlorinated biphenyls (PCBs) were measured at the CDC using gas chromatography/isotope dilution high-resolution mass spectrometry (Jones et al. 2012; Sjodin et

al. 2004). Serum samples were pretreated and extracted by solid phase extraction. Quality control (N=3) and method blank (N=3) samples were included in every batch of serum samples analyzed (N=24). PBDE concentrations were expressed on a serum lipid basis (ng/g lipid). Total lipids were determined based on serum measurements of triglycerides and total cholesterol using standard enzymatic methods (Phillips et al. 1989). The limit of detection (LOD) was defined as 3 times the standard deviation (SD) of the method blank samples analyzed in parallel with the study samples or in the absence of a detectable blank as 5 pg/μL. Values <LOD were substituted with the LOD/√2 (Hornung and Reed 1990).

Thyroid hormone analysis was conducted by the Department of Laboratory Medicine of the University of Washington. Specimens were immediately stored at -70°C upon arrival at the laboratory. Thyroid hormones and antibodies were quantified using an Access2 automated clinical immunoassay analyzer by Beckman Coulter, Inc. (Fullerton, CA). Two levels of quality control materials (BioRad Liquicheck or BioRad Immunoassay Plus [Hercules, CA]) were run with each assay every day (N=22). Coefficients of variation for assays for thyroid stimulating hormone (TSH), free thyroxine (FT₄), total thyroxine (TT₄), total triiodothyronine (TT₃), free triiodothyronine (FT₃), thyroid peroxidase (TPOAb), and thyroglobulin antibodies (TgAb) ranged from <0.1-11% (see Supplemental Material, Table S2). To ensure against transcription errors, results were double-checked by a second technologist.

Statistical analysis

We computed summary statistics for individual and total PBDEs (Σ PBDEs), defined as the sum of congeners with detection frequencies >50% (BDEs 28, 47, 99, 100, and 153). We evaluated correlations between PBDEs and thyroid hormones using Spearman rank-order correlation and analysis of variance to examine the relation between maternal and infant characteristics and

Σ PBDE concentrations. The distribution of PBDEs, PCBs, TSH, and thyroid antibodies were log normally distributed (Shapiro-Wilkes); therefore, concentrations of PBDEs and PCBs were \log_{10} -transformed, and TSH and thyroid antibodies were ln-transformed.

We used separate multiple linear regression models to estimate beta coefficients and 95% confidence intervals (CIs) for individual PBDE congeners with detection frequencies >50% and Σ PBDEs in relation to each thyroid hormone in maternal and cord sera. Covariates included in final regression models were based on results of bivariate analyses examining the relationship with thyroid hormone levels ($p < 0.20$). Final maternal serum models included the following covariates (categorized as shown in Table 2): maternal age at enrollment, race, education, parity, family income, smoking status, alcohol consumption, gestational age at thyroid hormone measurement (in weeks, continuous), and maternal serum PCB concentrations (the sum of congeners with detection frequencies >75%, including congeners-28, 74, 99, 105, 118, 146, 153, 156, 170, 180, 183, 187, 194, 199, and 206; \log_{10} -transformed, continuous). Cord serum models additionally included infant sex and mode of delivery. The following covariates were also considered, but did not meet our criteria for inclusion in the final models ($p < 0.20$): maternal blood lead levels, marijuana use, maternal country of birth, maternal depressive symptoms (Beck et al. 1996), vitamin intake (daily, <daily, never), and time of sample collection (hour of day). Percent changes in thyroid hormone concentrations associated with 10-fold increases in individual or Σ PBDEs were calculated by dividing the PBDE model coefficient by the mean thyroid hormone concentrations for the study sample (see Supplemental Material, Table S3).

We estimated dose-response models by linear regression for individual PBDE congeners using quartiles, with quartile 1 as the referent group. Linear trend was assessed by using the median value in each quartile as a continuous variable in the linear regression models (Greenland 1995).

We also examined the relation between prenatal PBDE exposure and thyroid antibody concentrations (TgAb or TPOAb) in maternal and cord sera using linear regression models. Since women or infants with impaired thyroid function may be more susceptible to the effects of PBDE exposure, we examined whether thyroid antibodies modified the association between PBDEs and thyroid hormones using product interaction terms between continuous PBDE concentrations and dichotomous TgAb or TPOAb ($p < 0.10$ considered significant). Few participants had clinically significant levels of TgAb (> 2.0 IU/mL; $N = 8$), modified from previous laboratory reference range (NHANES 2007a), or TPOAb (> 9.0 IU/mL; $N = 15$) (NHANES 2007b). Therefore, we dichotomized TPOAb at $>$ or \leq the median level and TgAb at detectable or not detectable. Stata version 12.1 (StataCorp, College Station, TX) was used for statistical analyses, and graphs were produced using GraphPad Prism (GraphPad, San Diego, CA). All tests of statistical significance were 2-sided, and $p < 0.05$ were considered significant.

Results

BDE-28, -47, -99, -100, and -153, major components of the penta mixture DE-71, had detection frequencies ranging from 80-100% (Table 1). The most abundant congener was BDE-47, with a geometric mean (GM) of 20.5 ng/g lipid. Concentrations of \sum PBDEs were higher among women who were younger, less educated, and of lower income (Table 2). Further, women who self-reported as non-Hispanic white had lower concentrations of \sum PBDEs (33.9 ± 2.6 ng/g lipid) compared to non-Hispanic blacks and others (53.7 ± 2.6 ng/g lipid). Although not statistically significant, concentrations of \sum PBDEs were higher among active smokers and women whose infants were < 2500 grams. As expected, PBDE congeners were highly correlated with each other and with \sum PBDEs ($r_s = 0.47-0.96$, $p < 0.001$) (see Supplemental Material, Table S4).

The GM of TSH was higher in cord serum (7.1 ± 1.8 uIU/mL) than in maternal serum (1.2 ± 2.2 uIU/mL) (see Supplemental Material, Table S3). Cord T_3 levels (51.5 ± 18.9 ng/dL) were approximately a third of maternal levels (160.5 ± 24.1 ng/dL). Maternal TSH was weakly positively correlated with cord TSH ($r_s = 0.26$; $p < 0.01$) (see Supplemental Material, Table S5). Positive correlations were observed between TT_4 and FT_4 , TT_3 , and FT_3 in maternal and cord sera.

Individual PBDE congeners and Σ PBDEs were inversely related to maternal serum concentrations of TSH; however, none of the associations were statistically significant (Table 3). We estimated significant increases in maternal TT_4 for each 10-fold increase of BDE-28 ($\beta = 0.85$ μ g/dL, 95% CI 0.05, 1.64) and BDE-47 ($\beta = 0.82$ μ g/dL, 95% CI 0.12, 1.51), corresponding to an 8% (95% CI 0.5%, 16%) and 8% (95% CI 1%, 15%) increase in mean maternal TT_4 , respectively. We also found that 10-fold increases in BDE-28 and -47 were associated with maternal FT_4 increases of 7% (95% CI 1%, 13%) and 6% (95% CI 1%, 10%), respectively. Ten-fold increases in BDE-28 and -47 were also associated with higher concentrations of maternal FT_3 ($\beta = 0.14$ pg/ml, 95% CI 0.02, 0.26 and $\beta = 0.12$ pg/ml, 95% CI 0.01, 0.22), which were equivalent to increases of 4% (95% CI 1%, 8%) and 4% (95% CI 0.3%, 7%) from the mean FT_3 , respectively. BDE-47 was significantly associated with maternal serum TT_3 ($\beta = 8.71$ ng/dL, 95% CI 0.42, 16.99), corresponding to an increase of 5% (95% CI 0.3%, 11%) from the mean maternal TT_3 level of 160.5 ng/dL. Concentrations of individual PBDE congeners were generally associated with lower concentrations of cord TSH, T_4 , and T_3 ; however, only one significant inverse association was observed between BDE-28 and FT_3 , with a 6% (95% CI -12%, -0.2%) decrease from the mean concentration of cord FT_3 for every 10-fold increase in BDE-28.

We observed a significant linear trend between quartiles of BDE-47 and concentrations of maternal free and total T₄ and T₃, particularly with TT₄ (p trend=0.006) (Figure 1). Significant linear trend was also observed with BDE-28 and maternal free and total T₄ and T₃; however, the pattern may suggest a nonmonotonic relationship. No significant linear trend was noted between BDE-28 or -47 quartiles and thyroid hormones in cord serum (see Supplemental Material, Figure S1).

No significant relationship was detected between PBDEs and thyroid antibody concentrations in maternal or cord serum (see Supplemental Material, Table S6). However, TgAb significantly modified ($p<0.10$) the association between PBDEs (BDE-47, -99, and Σ PBDEs) and cord TSH and FT₃ (see Supplemental Material, Table S7). PBDEs were negatively associated with cord TSH and FT₃ among women with detectable TgAb while associations were null for those with undetectable concentrations. We also observed that Σ PBDEs were associated with reductions in cord FT₄ concentrations if cord TPOAb was above the median (0.3 IU/mL), which may be due to a lower capacity of T₄ production, and subsequently lower transfer of T₄ to the fetus, in women with high TPOAb.

Discussion

We found that maternal concentrations of BDE-28 and -47 during pregnancy were associated with increased concentrations of maternal free and total T₄ and T₃ in the early second trimester of pregnancy. A 4-8% increase in maternal T₃ and T₄ levels from the study sample mean values was observed with 10-fold increases in BDE-28 and -47. This association may be due to structural similarities between these congeners and T₃ and T₄. BDE-28 and -47, which have three and four bromines on their two phenyl rings, more closely resemble T₃ and T₄, which contain three and four iodine atoms, respectively.

Although we estimated increases in mean T_3 and T_4 that are below clinical thresholds, the difference may not be trivial; small shifts in the distribution may have a substantial impact (Miller et al. 2009). In a longitudinal study of 16 healthy men, Andersen et al. (2002) obtained monthly serum samples for one year and observed that the width of the individual 95% CIs were approximately half that of the group for free and total T_4 , T_3 , and TSH, suggesting small shifts at a population level would be relatively large changes on an individual level. Further, the importance of this elevation is unclear, especially among subpopulations that may be more sensitive to thyroid hormone disruption, such as individuals with clinical or subclinical hyperthyroxinemia.

Our findings regarding TT_4 and FT_4 are similar to those reported by Stapleton et al. (2011), in which each 10-fold increase in BDE-47 was associated with higher maternal levels of TT_4 ($\beta=0.42$ $\mu\text{g/dL}$, 95% CI 0.05, 0.78) and FT_4 ($\beta=0.05$ ng/dL , 95% CI 0.01, 0.08) during the third trimester. We observed similar findings as Stapleton et al. (2011) regarding positive associations between maternal TT_4 and BDE-99 and -100, and FT_4 and BDE-153, but associations were not statistically significant (Table 3). A recent study of 260 Canadian women measured PBDE concentrations and thyroid hormones at 10.8 ± 2.7 weeks of gestation and reported similar results regarding PBDEs and FT_4 , finding BDE-47 ($\beta=0.02$ ng/dL , 95% CI 0.005, 0.03) and -99 ($\beta=0.02$ ng/dL , 95% CI 0.005, 0.04) were associated with increased concentrations of FT_4 during the first trimester (Abdelouahab et al. 2013). In contrast to our findings and those of Stapleton et al.'s, an inverse association was noted between PBDEs and maternal TT_4 in the Canadian study. Further, studies examining the role of PBDEs on thyroid hormone levels in men have likewise reported positive associations with TT_4 and FT_4 (Meeker et al. 2009; Turyk et al. 2008). A positive association between PBDEs and maternal TT_3 was also reported by Stapleton et al. (2011), in

which BDE-47 was associated with maternal TT₃ levels >178 ng/dL (OR=1.30, 95% CI 1.00, 1.69). However, an inverse association was estimated with serum concentrations of BDE-47 (β = -7.81 ng/dL, 95% CI -11.37, -4.26) and -99 (β = -4.19 ng/dL, 95% CI -8.26, -0.12) and maternal TT₃ by Abdelouahab et al. (2013), though an increase in maternal FT₃ with prenatal BDE-99 exposure was also reported (β =0.08 pmol/L, 95% CI 0.03, 0.13).

Consistent with other studies, we found no significant relation between PBDEs and TSH in maternal (Abdelouahab et al. 2013; Stapleton et al. 2011; Zhang et al. 2010) and cord sera (Abdelouahab et al. 2013; Herbstman et al. 2008; Kim et al. 2009b; Lin et al. 2011; Roze et al. 2009). In addition, our results are consistent with previous studies reporting no association between PBDEs and cord levels of free and total T₄, (Kim et al. 2009b; Lin et al. 2011; Mazdai et al. 2003; Roze et al. 2009). Cord serum analyses yielded one significant result between BDE-28 and FT₃. Only one previous study, conducted in a sample of 54 pregnant women in southern Taiwan, reported a reduction in FT₃ levels in cord serum with BDE-153 and -183 exposure (Lin et al. 2011). Although not statistically significant, prenatal PBDEs consistently had an inverse relationship with free and total T₄ and T₃ in cord serum in our study. This was unexpected given the increases observed in maternal thyroid hormones. However, inconsistent results between prenatal PBDEs and thyroid hormones in maternal and cord sera have also been reported by Abdelouahab et al. (2013). It is not certain what mechanisms would result in these contrasting findings. It is noteworthy that previous studies have focused on different gestational periods, and thyroid hormones are known to fluctuate during pregnancy (Soldin et al. 2004). Inconsistent conclusions between studies may be due to differences in timing of thyroid hormone measurements, an issue we attempted to address by controlling for gestational age at blood draw and using an exposure/outcome measure within a relatively narrow time window (16±3 weeks of

gestation). Differences in the exposure levels across populations could also explain discrepancies.

Most rodent models have shown a reduction in serum T₄ concentrations with PBDE exposure, suggesting a hypothyroxinemic effect (Richardson et al. 2008; Zhou et al. 2002), while human studies in nonpregnant cohorts suggest a hyperthyroid effect (Hagmar et al. 2001; Meeker et al. 2009; Turyk et al. 2008). Conflicting reports between animal and human studies may be due to physiological differences across species. Although hydroxylated-PBDEs (OH-PBDEs) were not measured in our study, these metabolites bind to TTR with high potency. However, the percentage of TTR-bound T₄ is comparatively lower in humans than in rodents since the major thyroid hormone transport protein in humans is thyroxine-binding globulin (TBG). The mechanisms by which PBDEs affect thyroid hormone action may be further complicated by the potential effects of various metabolites.

Most studies examining PBDEs and thyroid hormone levels have either studied pregnant women during late gestation or fetal levels of thyroid hormones in cord serum. To our knowledge, only one other study has examined PBDEs and thyroid hormones during the second trimester of pregnancy. However, this study had a rather small sample size of 25 pregnant women between 19-23 weeks of gestation (Zota et al. 2011). Chevrier et al.'s (2010) study population comprised of 270 pregnant women, but PBDEs were measured at 27.3 ± 3.1 weeks of gestation, the last week of the second trimester. Both studies reported null associations between prenatal PBDEs and free and total T₄, whereas positive associations were observed in this study. In addition, although our findings do not indicate a relation between PBDEs and maternal or cord TSH, Chevrier et al. (2010) reported a decrease in maternal TSH with 10-fold increases in BDE-100

exposure ($\beta=-0.09$ mIU/L, 95% CI -0.15, -0.02), while Zota et al. (2011) reported an increase with ln-BDE-85 ($\beta=0.33$ mIU/L, 95% 0.02, 0.64).

Our study has several strengths. We included data on numerous potentially confounding covariates, encompassing sociodemographic and behavioral factors, mode of delivery, time of sample collection, and PCB concentrations. Further, PBDE concentrations in our participants are comparable to pregnant women from the National Health and Nutrition Examination Survey (NHANES) during 2003-2004. The GM of BDE-47 in the NHANES pregnant women was 23.9 ng/g lipid (Woodruff et al. 2011) compared to 20.5 ng/g lipid observed in our study. The arithmetic mean concentration of BDE-28 among individuals aged 20-39 in NHANES 2007-2008 (1.5 ng/g lipid) (Sjodin et al. 2014) was also similar to our participants (1.8 ng/g lipid). In addition, thyroid hormone levels in the majority of our study participants are within the normal range for pregnant women (Soldin et al. 2004) and are similar to other study populations (Abdelouahab et al. 2013; Stapleton et al. 2011; Zota et al. 2011).

We examined interactions between PBDEs and thyroid antibodies. Ten-fold increases in certain PBDEs were associated with reductions in cord TSH and FT₃ if cord TgAb levels were detectable. Lower concentrations of cord FT₄ were observed with exposure to PBDEs at TPOAb levels above the median, which is biologically plausible given that women with high levels of TPOAb have a lower capacity for T₄ production and thus lower transfer of T₄ to the fetus.

Our findings are subject to several limitations. First, we were unable to examine OH-PBDEs, which may be more detrimental to the thyroid system than their parent congeners since OH-PBDEs more closely resemble T₃ and T₄, have a higher affinity to TBG and TTR (Marchesini et al. 2008; Meerts et al. 2000), and may increase deiodination of T₄ (Stapleton et al. 2009). Urinary

iodine was measured at 26 weeks gestation in a majority of study participants, which may not reflect the iodine levels at the time of thyroid hormone measurements (16 weeks gestation or at delivery) since iodine has a short half-life and varies substantially daily (Konig et al. 2011).

Therefore, we did not include iodine as a covariate.

Competitive binding may be an issue when utilizing immunoassays to measure thyroid hormones. Antibodies used to bind with thyroid hormones may also be able to bind with PBDEs as they are structurally similar, making PBDEs appear positively correlated with thyroid hormones. However, a positive association has been observed between PBDEs and T₃ levels in placental tissue measured by liquid chromatography-tandem mass spectrometry (Leonetti et al. 2014). Lastly, free thyroid hormones were measured using an immunoassay which may be subject to measurement error. Bound-T₄ (TBG attached T₄) increases during pregnancy and may affect immunoassay results (Wang et al. 2000). Equilibrium dialysis may be more appropriate as this method has been shown to yield accurate results regardless of elevated bound-T₄ concentrations (Nelson et al. 1994). Aside from Chevrier et al. (2010), no study examining prenatal PBDEs and thyroid hormones in maternal or cord serum has performed equilibrium dialysis. Limited volume of residual serum samples precluded us from further pursuing this method.

Conclusions

We observed that maternal serum BDE-28 and -47 levels were associated with increases in maternal serum concentrations of T₄ and T₃ during the early second trimester of pregnancy. However, the changes in thyroid concentrations were in the subclinical range and their potential impact is unclear. In contrast, we did not find that prenatal PBDE exposure was related to thyroid hormone concentrations in cord serum, nor was there evidence to suggest a relation between

PBDEs and thyroid hormone antibodies in maternal or cord serum. Future studies should focus on OH-PBDEs and thyroid hormones during early gestation. Additional research is also needed to explore mechanisms by which PBDEs and their metabolites exert their action on the thyroid system and to identify susceptible populations.

References

- Abdelouahab N, Langlois MF, Lavoie L, Corbin F, Pasquier JC, Takser L. 2013. Maternal and cord-blood thyroid hormone levels and exposure to polybrominated diphenyl ethers and polychlorinated biphenyls during early pregnancy. *Am J Epidemiol* 178:701-713.
- Andersen S, Pedersen KM, Bruun NH, Laurberg P. 2002. Narrow individual variations in serum T(4) and T(3) in normal subjects: A clue to the understanding of subclinical thyroid disease. *J Clin Endocrinol Metab* 87:1068-1072.
- Beck AT, Steer RA, Brown GK. 1996. Beck depression inventory. 2nd ed. San Antonio, TX:Psychological Corporation.
- Chevrier J, Harley KG, Bradman A, Gharbi M, Sjodin A, Eskenazi B. 2010. Polybrominated diphenyl ether (PBDE) flame retardants and thyroid hormone during pregnancy. *Environ Health Perspect* 118:1444-1449.
- Costa LG, Giordano G. 2007. Developmental neurotoxicity of polybrominated diphenyl ether (PBDE) flame retardants. *Neurotoxicology* 28:1047-1067.
- Dallaire R, Dewailly E, Pereg D, Dery S, Ayotte P. 2009. Thyroid function and plasma concentrations of polyhalogenated compounds in Inuit adults. *Environ Health Perspect* 117:1380-1386.
- Darnerud PO. 2008. Brominated flame retardants as possible endocrine disrupters. *Int J Androl* 31:152-160.
- de Escobar GM, Obregon MJ, del Rey FE. 2004. Maternal thyroid hormones early in pregnancy and fetal brain development. *Best Pract Res Clin Endocrinol Metab* 18:225-248.
- Forhead AJ, Fowden AL. 2014. Thyroid hormones in fetal growth and parturition. *J Endocrinol*.
- Greenland S. 1995. Avoiding power loss associated with categorization and ordinal scores in dose-response and trend analysis. *Epidemiology* 6:450-454.
- Hagmar L, Bjork J, Sjodin A, Bergman A, Erfurth EM. 2001. Plasma levels of persistent organohalogenated compounds and hormone levels in adult male humans. *Arch Environ Health* 56:138-143.
- Henrichs J, Ghassabian A, Peeters RP, Tiemeier H. 2013. Maternal hypothyroxinemia and effects on cognitive functioning in childhood: How and why? *Clin Endocrinol (Oxf)* 79:152-162.

- Herbstman JB, Sjodin A, Apelberg BJ, Witter FR, Halden RU, Patterson DG, et al. 2008. Birth delivery mode modifies the associations between prenatal polychlorinated biphenyl (PCB) and polybrominated diphenyl ether (PBDE) and neonatal thyroid hormone levels. *Environ Health Perspect* 116:1376-1382.
- Hornung RW, Reed LD. 1990. Estimation of average concentration in the presence of nondetectable values. *Applied Occupational and Environmental Hygiene* 5:46-51.
- Jones R, Edenfield E, Anderson S, Zhang Y, Sjodin A. 2012. Semi-automated extraction and cleanup method for measuring persistent organic pollutants in human serum. *Organohalogen Compd* 74:97-98.
- Julvez J, Alvarez-Pedrerol M, Rebagliato M, Murcia M, Fornes J, Garcia-Esteban R, et al. 2013. Thyroxine levels during pregnancy in healthy women and early child neurodevelopment. *Epidemiology* 24:150-157.
- Kim TH, Lee YJ, Lee E, Kim MS, Kwack SJ, Kim KB, et al. 2009a. Effects of gestational exposure to decabromodiphenyl ether on reproductive parameters, thyroid hormone levels, and neuronal development in Sprague-Dawley rats offspring. *J Toxicol Environ Health A* 72:1296-1303.
- Kim TH, Lee YJ, Lee E, Patra N, Lee J, Kwack SJ, et al. 2009b. Exposure assessment of polybrominated diphenyl ethers (PBDE) in umbilical cord blood of Korean infants. *J Toxicol Environ Health A* 72:1318-1326.
- Kim UJ, Lee IS, Kim HS, Oh JE. 2011. Monitoring of pbdes concentration in umbilical cord blood and breast milk from Korean population and estimating the effects of various parameters on accumulation in humans. *Chemosphere* 85:487-493.
- Konig F, Andersson M, Hotz K, Aeberli I, Zimmermann MB. 2011. Ten repeat collections for urinary iodine from spot samples or 24-hour samples are needed to reliably estimate individual iodine status in women. *J Nutr* 141:2049-2054.
- Leonetti C, Hoffman K, Miranda ML, Stanton ME. 2014. Associations between PBDEs, 2,4,6 tribromophenol and thyroid hormone levels in human placental tissues. In: 14th Annual Workshop on Brominated & Other Flame Retardants (BFR). Indianapolis, IN.
- Lin SM, Chen FA, Huang YF, Hsing LL, Chen LL, Wu LS, et al. 2011. Negative associations between PBDE levels and thyroid hormones in cord blood. *Int J Hyg Environ Health* 214:115-120.

- Mannisto T, Mendola P, Grewal J, Xie Y, Chen Z, Laughon SK. 2013. Thyroid diseases and adverse pregnancy outcomes in a contemporary US cohort. *J Clin Endocrinol Metab* 98:2725-2733.
- Marchesini GR, Meimaridou A, Haasnoot W, Meulenberg E, Albertus F, Mizuguchi M, et al. 2008. Biosensor discovery of thyroxine transport disrupting chemicals. *Toxicol Appl Pharmacol* 232:150-160.
- Mazdai A, Dodder NG, Abernathy MP, Hites RA, Bigsby RM. 2003. Polybrominated diphenyl ethers in maternal and fetal blood samples. *Environ Health Perspect* 111:1249-1252.
- Meeker JD, Johnson PI, Camann D, Hauser R. 2009. Polybrominated diphenyl ether (PBDE) concentrations in house dust are related to hormone levels in men. *Sci Total Environ* 407:3425-3429.
- Meerts IA, van Zanden JJ, Luijckx EA, van Leeuwen-Bol I, Marsh G, Jakobsson E, et al. 2000. Potent competitive interactions of some brominated flame retardants and related compounds with human transthyretin in vitro. *Toxicol Sci* 56:95-104.
- Miller MD, Crofton KM, Rice DC, Zoeller RT. 2009. Thyroid-disrupting chemicals: Interpreting upstream biomarkers of adverse outcomes. *Environ Health Perspect* 117:1033-1041.
- Morreale de Escobar G, Obregon MJ, Escobar del Rey F. 2000. Is neuropsychological development related to maternal hypothyroidism or to maternal hypothyroxinemia? *J Clin Endocrinol Metab* 85:3975-3987.
- Nelson JC, Weiss RM, Wilcox RB. 1994. Underestimates of serum free thyroxine (T4) concentrations by free T4 immunoassays. *J Clin Endocrinol Metab* 79:76-79.
- NHANES. 2007a. Laboratory procedure manual: Thyroglobulin antibodies in serum. Available: http://www.cdc.gov/nchs/data/nhanes/nhanes_07_08/THYROD_e_met_Thyroglobulin_Antibodies.pdf [accessed April 2 2015].
- NHANES. 2007b. Laboratory procedure manual: Thyroid peroxidase antibodies in serum. Available: http://www.cdc.gov/nchs/data/nhanes/nhanes_07_08/THYROD_e_met_Thyroid_Peroxidase_Antibodies.pdf [accessed April 2 2015].
- Phillips DL, Pirkle JL, Burse VW, Bernert JT, Jr., Henderson LO, Needham LL. 1989. Chlorinated hydrocarbon levels in human serum: Effects of fasting and feeding. *Arch Environ Contam Toxicol* 18:495-500.

- Richardson VM, Staskal DF, Ross DG, Diliberto JJ, DeVito MJ, Birnbaum LS. 2008. Possible mechanisms of thyroid hormone disruption in mice by BDE 47, a major polybrominated diphenyl ether congener. *Toxicol Appl Pharmacol* 226:244-250.
- Roze E, Meijer L, Bakker A, Van Braeckel KN, Sauer PJ, Bos AF. 2009. Prenatal exposure to organohalogens, including brominated flame retardants, influences motor, cognitive, and behavioral performance at school age. *Environ Health Perspect* 117:1953-1958.
- Sjodin A, Jones RS, Lapeza CR, Focant JF, McGahee EE, 3rd, Patterson DG, Jr. 2004. Semiautomated high-throughput extraction and cleanup method for the measurement of polybrominated diphenyl ethers, polybrominated biphenyls, and polychlorinated biphenyls in human serum. *Anal Chem* 76:1921-1927.
- Sjodin A, Jones RS, Caudill SP, Wong LY, Turner WE, Calafat AM. 2014. Polybrominated diphenyl ethers, polychlorinated biphenyls, and persistent pesticides in serum from the National Health and Nutrition Examination Survey: 2003-2008. *Environ Sci Technol* 48:753-760.
- Soldin OP, Tractenberg RE, Hollowell JG, Jonklaas J, Janicic N, Soldin SJ. 2004. Trimester-specific changes in maternal thyroid hormone, thyrotropin, and thyroglobulin concentrations during gestation: Trends and associations across trimesters in iodine sufficiency. *Thyroid* 14:1084-1090.
- Stapleton HM, Kelly SM, Pei R, Letcher RJ, Gunsch C. 2009. Metabolism of polybrominated diphenyl ethers (PBDEs) by human hepatocytes in vitro. *Environ Health Perspect* 117:197-202.
- Stapleton HM, Eagle S, Anthopolos R, Wolkin A, Miranda ML. 2011. Associations between polybrominated diphenyl ether (PBDE) flame retardants, phenolic metabolites, and thyroid hormones during pregnancy. *Environ Health Perspect* 119:1454-1459.
- Turyk ME, Persky VW, Imm P, Knobeloch L, Chatterton R, Anderson HA. 2008. Hormone disruption by PBDEs in adult male sport fish consumers. *Environ Health Perspect* 116:1635-1641.
- Wang R, Nelson JC, Weiss RM, Wilcox RB. 2000. Accuracy of free thyroxine measurements across natural ranges of thyroxine binding to serum proteins. *Thyroid* 10:31-39.
- Woodruff TJ, Zota AR, Schwartz JM. 2011. Environmental chemicals in pregnant women in the United States: NHANES 2003-2004. *Environ Health Perspect* 119:878-885.

- Zhang J, Jiang Y, Zhou J, Wu B, Liang Y, Peng Z, et al. 2010. Elevated body burdens of PBDEs, dioxins, and PCBs on thyroid hormone homeostasis at an electronic waste recycling site in China. *Environ Sci Technol* 44:3956-3962.
- Zhou T, Taylor MM, DeVito MJ, Crofton KM. 2002. Developmental exposure to brominated diphenyl ethers results in thyroid hormone disruption. *Toxicol Sci* 66:105-116.
- Zota AR, Park JS, Wang Y, Petreas M, Zoeller RT, Woodruff TJ. 2011. Polybrominated diphenyl ethers, hydroxylated polybrominated diphenyl ethers, and measures of thyroid function in second trimester pregnant women in California. *Environ Sci Technol* 45:7896-7905.

Table 1. Concentrations of polybrominated diphenyl ether congeners (ng/g lipid) around the 16th week of pregnancy, HOME Study.

PBDEs	<i>n</i>	Percent detection	Min	Percentile				Max	GM (GSD)	NHANES ^a GM (GSD)
				25th	50th	75th	95th			
ΣPBDEs ^{b,c}	274	100.0 ^d	4.5	20.8	36.0	75.1	213.7	2046.9	40.0 (2.6)	NA
BDE-17	275	3.3	0.1	0.3	0.3	0.4	1.0	4.0	NA	NA
BDE-28 ^c	275	80.0	0.2	0.6	1.0	1.7	4.8	31.4	1.1(2.4)	1.5 (0.3) ^e
BDE-47 ^c	305	100.0	1.5	10.8	19.1	35.3	103	1290	20.5 (2.7)	23.9 (2.2)
BDE-66	275	1.8	0.1	0.3	0.3	0.4	1.1	2.6	NA	NA
BDE-85	275	49.5	0.2	0.3	0.5	1.0	3.7	38.7	NA	NA
BDE-99 ^c	294	99.3	0.6	2.5	4.4	8.8	32.8	465	4.9 (2.9)	5.5 (0.8)
BDE-100 ^c	275	98.2	0.4	2.1	3.7	7.9	27.6	172	4.1 (2.9)	6.1 (0.9)
BDE-153 ^c	274	99.3	0.5	2.7	4.5	9.0	50.8	152	5.5 (2.9)	9.9 (3.0)
BDE-154	275	44.7	0.2	0.3	0.5	1.0	3.0	28.7	NA	NA
BDE-183	275	22.9	0.1	0.3	0.4	0.5	1.2	9.3	NA	NA

Abbreviations: GM, geometric mean; GSD, geometric standard deviation; Max, maximum; Min, minimum; NA, not available (percent detection <50%).

^aSerum concentrations in NHANES 2003-2004 pregnant women (Woodruff et al. 2011). ^bIncludes congeners with detection frequencies >50% (BDEs 28, 47, 99, 100, and 153). ^cIncluded in statistical analyses. ^dPercentage of samples with at least one congener above the LOD. ^eArithmetic mean concentration among NHANES 2007-2008 individuals ages 20-39 (Sjodin et al. 2014)

Table 2. Serum concentrations of total polybrominated diphenyl ethers^a (ng/g lipid) by demographic characteristics, HOME Study.

Characteristic	<i>n</i> (%) ^b	Geometric Mean (GSD)
Age, years		
<25	64 (23.3)	47.1(2.2) [*]
25-34	165 (60.2)	41.2(2.8)
≥35	45 (16.4)	28.4(2.5)
Race/ethnicity		
Non-Hispanic White	175 (64.3)	33.9(2.6) ^{**}
Non-Hispanic Black and Others	97 (35.7)	53.7(2.6)
Education		
High school or less	71 (26.1)	56.4(2.3) ^{**}
Some college or 2 year degree	65 (23.9)	42.6(2.3)
Bachelor's	84 (30.9)	34.1(2.7)
Graduate or professional	52 (19.1)	29.7(3.1)
Parity		
Nulliparous	126 (46.0)	35.5(2.7)
Primiparous	81 (29.6)	42.8(2.5)
Multiparous	67 (24.4)	45.8(2.7)
Mode of Delivery		
Vaginal	173 (63.1)	42.1(2.5)
Planned Cesarean	58 (21.1)	37.5(3.1)
Emergency Cesarean	18 (6.6)	26.1(2.9)
Assisted Vaginal	25 (9.1)	43.7(2.1)
Breastfeeding current child		
No	52 (19.6)	42.7(2.2)
Yes	213 (80.4)	39.2(2.7)
Breastfed previous child(ren)		
No	36 (25.7)	53.1(2.4)
Yes	104 (74.3)	40.7(2.5)
Family Income		
<\$40,000	106 (39.0)	52.0(2.6) ^{**}
\$40,000-\$79,999	90 (33.1)	38.3(2.6)
≥\$80,000	76 (27.9)	29.2(2.5)
Smoking Status		
No	225 (82.1)	38.0(2.7)
Environmental Tobacco Smoke	26 (9.5)	43.1(2.2)
Active	23 (8.4)	59.2(2.4)
Alcohol Consumption		
Never	154 (56.6)	41.4(2.6)
<1 Alcoholic Drink per Month	82 (30.1)	37.1(2.7)
>1 Alcoholic Drink per Month	36 (13.2)	40.7(2.8)
Marijuana Use		

No	251 (92.3)	39.2(2.7)
Yes	21 (7.7)	50.3(2.4)
Infant Gender		
Male	122 (44.5)	37.0(2.6)
Female	152 (55.5)	42.5(2.7)
Birth weight, grams		
<2,500	13 (4.7)	51.1(2.7)
2,500-3,500	145 (52.9)	41.1(2.5)
>3,500	116 (42.3)	37.5(2.8)

Abbreviations: GSD, geometric standard deviation.

* $p < 0.05$, ** $p < 0.001$ (two-sided p values using ANOVA)

^aSum of congeners with detection frequencies >50% (BDEs 28, 47, 99, 100, and 153). ^bFrequencies may not add to the total number of participants because of missing values. Percentages may not add to 100% because of rounding.

Table 3. Adjusted associations between maternal polybrominated diphenyl ether concentrations and maternal and cord sera levels of thyroid hormones, HOME Study.^a

PBDEs	Maternal Serum ^b		Cord Serum ^{b,c}	
	N	β (95% CI)	N	β (95% CI)
lnTSH				
BDE-28	165	-0.07 (-0.40, 0.26)	228	-0.04 (-0.24, 0.16)
BDE-47	165	-0.14 (-0.43, 0.15)	228	-0.10 (-0.28, 0.07)
BDE-99	165	-0.12 (-0.40, 0.16)	228	-0.16 (-0.33, 0.01)
BDE-100	165	-0.09 (-0.37, 0.18)	228	-0.04 (-0.21, 0.12)
BDE-153	165	-0.10 (-0.35, 0.16)	227	0.06 (-0.10, 0.22)
Σ PBDEs	165	-0.11 (-0.41, 0.19)	227	-0.08 (-0.26, 0.10)
TT ₄				
BDE-28	165	0.85 (0.05, 1.64)*	224	-0.13 (-0.78, 0.52)
BDE-47	165	0.82 (0.12, 1.51)*	224	-0.15 (-0.72, 0.43)
BDE-99	165	0.49 (-0.19, 1.16)	224	-0.08 (-0.63, 0.48)
BDE-100	165	0.55 (-0.12, 1.22)	224	-0.15 (-0.69, 0.39)
BDE-153	165	0.07 (-0.56, 0.70)	223	-0.08 (-0.60, 0.45)
Σ PBDEs	165	0.61 (-0.11, 1.33)	223	-0.15 (-0.74, 0.44)
TT ₃				
BDE-28	165	9.34 (-0.19, 18.88)	228	-4.34 (-10.76, 2.07)
BDE-47	165	8.71 (0.42, 16.99)*	228	-1.71 (-7.39, 3.97)
BDE-99	165	6.30 (-1.70, 14.30)	228	-0.47 (-5.97, 5.04)
BDE-100	165	7.04 (-0.93, 15.01)	228	-0.58 (-5.94, 4.77)
BDE-153	165	1.15 (-6.35, 8.65)	227	2.03 (-3.17, 7.23)
Σ PBDEs	165	6.38 (-2.23, 14.99)	227	-0.47 (-6.32, 5.38)
FT ₄				
BDE-28	165	0.05 (0.01, 0.09)*	228	-0.04 (-0.09, 0.02)
BDE-47	165	0.04 (0.004, 0.07)*	228	-0.03 (-0.07, 0.02)
BDE-99	165	0.02 (-0.01, 0.05)	228	-0.01 (-0.05, 0.03)
BDE-100	165	0.02 (-0.01, 0.05)	228	-0.03 (-0.07, 0.02)
BDE-153	165	0.004 (-0.03, 0.04)	227	-0.03 (-0.07, 0.02)
Σ PBDEs	165	0.03 (-0.01, 0.06)	227	-0.04 (-0.08, 0.01)
FT ₃				
BDE-28	165	0.14 (0.02, 0.26)*	226	-0.11 (-0.21, -0.003)*
BDE-47	165	0.12 (0.01, 0.22)*	226	-0.06 (-0.15, 0.03)
BDE-99	165	0.07 (-0.03, 0.17)	226	-0.03 (-0.12, 0.06)
BDE-100	165	0.08 (-0.02, 0.18)	226	-0.04 (-0.13, 0.05)
BDE-153	165	0.001 (-0.09, 0.10)	225	-0.01 (-0.09, 0.08)
Σ PBDEs	165	0.10 (-0.01, 0.21)	225	-0.05 (-0.14, 0.04)

* $p < 0.05$

^aUnits: PBDEs (ng/g lipid), TSH (uIU/mL), TT₄ (μg/dL), TT₃ and FT₄ (ng/dL), and FT₃ (pg/mL). PBDEs were log₁₀-transformed. ^bAdjusted for maternal age, race/ethnicity, education, parity, family income, smoking status, alcohol consumption, gestational age at blood draw, and total serum PCB concentrations.

^cAdditionally adjusted for infant gender and mode of delivery.

Figure Legend

Figure 1. β -coefficients and 95% CIs from regression models for associations of BDE-28 and BDE-47 (ng/g lipid) quartiles and maternal thyroid hormones. All models adjusted for maternal age, race/ethnicity, education, parity, family income, smoking status, alcohol consumption, gestational age at serum collection, and total serum PCB concentrations. *P* trend was obtained by using the median value in each quartile as a continuous variable in the linear regression models.

Figure 1.

